92460

4

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 April 2003 (17.04.2003)

PCT

(10) International Publication Number
WO 03/032336 A1

(51) **International Patent Classification**[7]: H01F 1/00, G11C 11/16

(21) **International Application Number:** PCT/EP02/11168

(22) **International Filing Date:** 4 October 2002 (04.10.2002)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
01123901.9 5 October 2001 (05.10.2001) EP
60/326,999 5 October 2001 (05.10.2001) US

(71) **Applicant** *(for all designated States except US)*: **UNIVERSITÄT REGENSBURG** [DE/DE]; 93040 Regensburg (DE).

(71) **Applicants and**
(72) **Inventors: HOFFMANN, Horst** [DE/DE]; Ahornstrasse 7, 93080 Pentling (DE). **ZWECK, Josef** [DE/DE]; Höflinger Ring 68, 93083 Obertraubling (DE).

(72) **Inventor; and**
(75) **Inventor/Applicant** *(for US only)*: **SCHNEIDER, Markus** [DE/DE]; Hopfenstrasse 4, 93152 Schönhofen (DE).

(74) **Agent: VOSSIUS & PARTNER**; Siebertstrasse 4, 81675 München (DE).

(81) **Designated States** *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

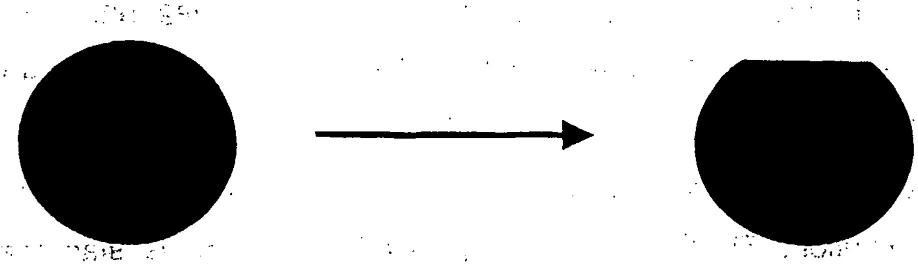
(84) **Designated States** *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

WO 03/032336 A1

(54) Title: MAGNETIC ELEMENTS WITH MAGNETIC FLUX CLOSURE, PRODUCTION METHOD AND MEMORY APPLICATION



(57) Abstract: The invention provides magnetic elements and memory cells. Magnetic vortices play an important role in the switching behaviour of micron- and submicron-sized ferromagnetic elements. Submicron permalloy elements are prepared by a combination of electron-beam lithography and liftoff technique on electron transparent membrane substrates. The magnetization reversal mechanism and the remanent magnetization configuration are observed by means of Lorentz transmission electron microscopy. In remanence, the investigated structures form a vortex configuration. The sense of magnetization rotation of the vortex configuration can be controlled by introducing a slight geometric asymmetry to the otherwise circular nanostructures.

MAGNETIC ELEMENTS WITH MAGNETIC FLUX CLOSURE, PRODUCTION METHOD AND MEMORY APPLICATION

Field of the invention

The present invention relates to a magnetic element comprising a magnetic vortex configuration in remanence and to its method of production. The invention further relates to a memory cell comprising such magnetic elements, in particular to a magnetic random access memory (MRAM).

Background of the invention

The reason progress in the development of non-volatile memories, like magnetic random access memory (MRAM), has increased the interest in the micromagnetic state of small ferromagnetic structures, like ferromagnetic nanostructures. In a number of publications it was shown that a reduction of the lateral size of magnetic elements causes more complex magnetization configurations than in the case of thin, continuous films. A key role in the magnetization reversal process play vortices which rule the switching of submicron particles (M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. 77, 2909 (2000); K. J. Kirk, M. R. Scheinfein, J. N. Chapman, S. McVitie, M. F. Gillies, B. R. Ward, and J. G. Tennant, J. Phys. D 32, 160 (2001)). Previous studies have shown that thin, circular nanostructures can be in a vortex state in zero applied magnetic field (T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Science 289, 930 (2000); J. Raabe, R. Pulwey, R. Sattler, T. Schweinböck, J. Zweck, and D. Weiss, J. Appl. Phys. 88, 4437 (2000)). Applying a magnetic field leads to a shift of the vortex core perpendicular to the field direction and to a distortion of the circular magnetization distribution. The sense of magnetization rotation is statistically distributed clockwise or counterclockwise, but can not be controlled on purpose in

the circular elements by the application of magnetic in-plane fields.

So far, ring- or disk-shaped elements with vortex magnetization or elongated elements having aspect ratios of more than 1 and high remanent magnetization, are considered options for future non-volatile memory cells. In case of ring- or disk-shaped elements switching of the elements may occur by means of current flowing through the elements whereas elongated elements may be switched by means of magnetic fields occurring from two crossed or paired conductor lines, i.e., the so-called word line and bit line, through which current flows.

In the article “Vortex circulation control in mesoscopic ring magnets”, Appl. Phys. Lett. 78, No.21, page 3268, a method is suggested to control the direction of the circulation of the magnetization in mesoscopic ring magnets, using a uniform magnetic field only. The method is based on the nucleation-free switching, which occurs when the rings switch from the near-saturated state, referred to as the "onion state", to the flux-closed vortex state. Two possible onion states, forward or reverse magnetized, are possible for a given direction of the magnetic field. Going from the forward or the backward onion state, both local scanning Kerr microscopy measurements and micromagnetic simulations suggest that the clockwise or the counterclockwise vortex state, respectively, can be selected due to asymmetric pinning of the two domain walls that are present in the onion state. In the simulation, a notch is introduced to pin one of the walls more strongly than the other.

In the article "Switching of vertical giant magnetoresistance devices by current through the device", Appl. Phys. Lett. 75, No. 16, page 2476, experiments are reported that suggest that current-perpendicular-to-the-plane giant magneto-resistance devices can be switched repeatedly between the high- and low-resistance states by passing current vertically through the structure. The

lithographically patterned devices are set to operate at room temperature and exhibit distinctly separate switching of the soft and hard layers. It is suggested that designs for magnetoelectronic random access memory can utilize this scheme for storing and reading information.

A general overview on magnetoelectronics applications is given in "Journal of Magnetism and Magnetic Materials" 200 (1999), pages 57-68.

US-A-5 969 978 discloses a memory architecture for a regular array of non-volatile ferromagnetic random access annular memory elements which can be based on the giant magnetoresistance effect.

US-A-6 153 443 describes a method of fabricating a magnetic random access memory positioned on circuitry for control of the memory element, which is formed under a complementary metal oxide semiconductor (CMOS) process.

WO 00/58970 describes a device including a magnetic material having a magnetization configuration that is circular in a plane, and a word line for producing a magnetic field in the plane, the magnetic field being radial with respect to a point in the plane and within the circular magnetization configuration.

US-A-6 104 633 relates to magnetic memory cells that include a changeable magnetic region with a magnetic axis along which two directions of magnetization can be imposed, thereby providing two respective states into which the cells are changeable according to electrical and resultant magnetic stimuli applied thereto. Asymmetry in the magnetic stimuli applied to the cell by writing a state therein is disclosed to provide a predictable magnetization pattern evolution from the first direction to the second direction. Physical asymmetry in the layout and/or magnetization of the cell is also suggested to provide the predictable pattern

evolution. These principles can be applied to magnetic random access memory arrays which employ magnetic tunnel junction cells at the intersections of bitlines and wordlines which supply the electrical and resultant magnetic stimuli to write the cells therein.

Summary of the invention

It is an object of the present invention to provide magnetic elements comprising a magnetization pattern having a magnetic flux closure, in particular magnetic single vortex elements, in which the sense of magnetization rotation can be influenced and controlled.

It is a further object of the invention to provide a method of producing such magnetic elements and to provide memory cells comprising such magnetic elements in which the sense of magnetization rotation can be controlled.

The present invention is based on the finding that the sense of rotation of a magnetic vortex or vortex-like configuration can be controlled by introducing a slight asymmetry into the geometric shape of the elements and applying a magnetic field to said asymmetric elements. In the present application, the term "vortex" is meant to include any magnetization pattern having a magnetic flux closure, including circular flux closures and Landau-Lifshiftz domain configurations, in small structures, in particular submicron structures.

The magnetic element according to the present invention comprises at least one magnetic particle. Preferably the magnetic element comprises a generally circular structure having a slight geometric asymmetry. For example, the magnetic element is disk-shaped having one flattened side or edge such that a segment of

the circular disk is removed. The length of said edge or chord is preferably about 1/4 to 3/4, more preferably about 1/2 to 2/3 of the diameter of the disk.

The disk may have a diameter of about 100-2000 nm, preferably 200-1000 nm, more preferably about 400-900 nm, most preferably about 600-800 nm. The thickness of the disk may be about 1-20 nm, preferably about 2-10 nm, about 5-9 nm and about 6-8 nm.

The magnetic element of the present invention has substantially zero net remanent magnetization, and the magnetic vortex or vortex-like configuration is stable against magnetic fields that are smaller than the saturation field of the element. The magnetic vortex may be produced by magnetization in an in-plane magnetic field up to the saturation of the elements. The magnetic field used to produce the vortex may be a homogeneous in-plane field.

The magnetic element of the present invention can be made of any type of ferromagnetic material, comprising Fe, Ni, Co and/or alloys thereof.

The magnetic element of the present invention can be produced on electron transparent membranes, like Si_3N_4 membranes, by a combination of electron beam lithography and liftoff technique. The flat edge of the circular disk can be produced, e.g., by irradiation using a linear pattern.

Magnetic elements of the present invention can be used to provide a memory cell, in particular a non-volatile memory cell. In such a memory cell the two senses of magnetization rotation of the magnetic element according to the present invention may define one bit of information.

A preferred memory cell of the present invention may comprise a stack of at least

two magnetic elements with different saturation fields. According to the invention multi-bit data storage cells may be formed from such stacks.

The magnetic element of the present invention can be used in various types of memory systems, including giant magnetoresistance systems, spin valve systems and/or magnetic tunnel junction systems. Preferably the memory elements of the present invention are used in a magnetic random access memory (MRAM).

Whereas infinitely symmetrical elements, after saturation in a magnetic in-plane field, have a magnetic vortex in remanence whose rotational sense cannot be deliberately adjusted, the sense of the magnetization rotation of the particles of the present invention can be controlled and/or adjusted by means of a magnetic in-plane field. The rotational sense of the magnetic vortex in clockwise and counter-clockwise direction describes the binary states "0" and "1", respectively. In order to control the sense of magnetization rotation symmetric particles are provided with a slight asymmetry. For example, an infinitely symmetrical circular disk can be provided with a flat or straight edge. In the present invention it has been shown that, as a consequence of the geometric asymmetry, the sense of magnetization rotation in a state without magnetic field can be controlled by the direction of the previously applied magnetic in-plane saturation field.

Using the geometrically asymmetric magnetic elements of the present invention having a controlled sense of rotation of the magnetic vortex provides several advantages.

Due to the magnetic vortex the magnetic elements of the present invention have none or only small net magnetization, and thus none or negligible stray fields.

Magnetic stray fields that can occur, e.g., when writing or addressing neighboring

bits in memory media with high density, and which are smaller than the saturation field strength of the magnetic particles, may deform the vortex but do not change its sense of rotation. Since the deformation disappears when the stray field is no longer present, the sense of rotation will be maintained and information will thus not be destroyed.

The direction of the magnetic vortex can be changed by a homogeneous in-plane magnetic field whereas in known concepts, like disclosed in US-A-5 969 978, a circular magnetic field is required which is provided via a current supplied through the element or a current running in the center of a ring. The high current density used in prior art devices may lead to a permanent destruction of the element and thus loss of information, e.g. by destroying the tunnel barrier in a magnetic tunnel junction device.

With the elements of the present invention both current-in-plane (CIP) as well as current-perpendicular-to-plane (CPP) elements can be provided.

By combining a plurality of such elements in a stack, devices may be produced whose information content is more than 1 bit. This provides a higher storage density. The layers of the stack can be switched separately by using elements which require different magnetic field strengths for switching.

The saturation and/or switching fields can be adjusted, e.g., by selecting the dimensions of the particles or the use of appropriate materials.

In the present specification the following definitions will be used, unless provided otherwise:

"Magnetic particle": a three dimensional object comprising or consisting of at least

one magnetic material.

"Magnetic element": a device containing at least one magnetic particle and being suitable for use in magnetic storage media or sensors.

"Magnetic vortex": magnetization pattern of a magnetic particle or element having no or small net magnetic moment.

"Remanent magnetization": magnetization of a magnetic object in a magnetic field-free state after switching off an applied magnetic field.

"GMR" or "giant magneto resistance": multilayer system of electrically conductive layers which are alternatingly magnetic and non-magnetic. The magnetic layers are coupled by an interlayer exchange coupling. The electric resistance through a GMR system depends on the relative orientation of the directions of magnetization in the magnetic layers.

"SV" or "spin valve": sandwich system consisting of at least two magnetic electrodes which are separated by a non-magnetic intermediate layer and which are not or only magnetostatically coupled. The electric resistance depends on the relative orientation of the directions of the magnetization in the magnetic layers.

"MTJ" or "magnetic tunnel junction": sandwich system consisting of at least two magnetic electrodes which are separated by a thin non-magnetic isolating layer which provides a tunnel barrier. The electric resistance perpendicular to the sandwich system depends on the relative orientation of the direction of magnetization in the magnetic electrodes.

Preferred embodiments and best mode for carrying out the invention

Preferred embodiments of the invention will be now described in connection with the drawings.

Figure 1 shows a circular disk having a flat edge providing geometric asymmetry.
Figure 2 shows underfocused Lorentz microscopy images of asymmetric circular dots at remanence after the application of a magnetic field |H| = 200 Oe in –x (a) and in +x (b) direction.
Figure 3 shows magnetization reversal of asymmetric circular dots with the in-plane field H applied parallel to the flat edge (x-direction)
Figure 4 shows a comparison of two magnetic element nanostructures with different saturation fields.
Figure 5 shows a model for the evolution of the vortex.
Figure 6 shows the current flow for current-in-plane (CIP) and current-perpendicular-to-plane (CPP) geometry.
Figure 7 shows a CPP memory cell with various orientations of magnetization.
Figure 8 shows the addressing of a memory cell.
Figure 9 shows schematically the magnetization in the magnetic elements of the invention.
Figures 10A and 10B show the provision of a magnetic field for writing in a memory cell.
Figure 11 shows a multilayer stack having a plurality of magnet/non-magnet transitions between layers.

Magnetic elements of the present invention made of permalloy (Py, $Ni_{80}Fe_{20}$) are fabricated on electron transparent Si_3N_4membranes by a combination of electron beam lithography, thermal evaporation of the Py and liftoff technique, in order to obtain information about the magnetization configuration.

The evaporated polycrystalline Py elements are, e.g., 8.3nm thick and have a lateral average grain size of, e.g., 7-10 nm, determined by bright field transmission electron microscopy. The micromagnetic structure of the Py nanostructures is investigated by means of Lorentz transmission electron microscopy (LTEM). The Fresnel mode of LTEM is used to obtain micromagnetic information about the remanent state and the magnetization reversal of dots prepared from disks (diameter e.g. 700 nm) with one flat edge. The Fresnel mode is a defocused technique where contrast is formed at sites where the variation of the magnetization direction is strongest, which means that domain walls would lead to bright and dark lines whereas vortices cause bright and dark spots at the position of the vortex core in the images. The special Lorentz lens in a Philips Tecnai F30 electron microscope that is used equipped with a field emission gun, allows experiments in magnetic field-free conditions when the standard objective lens is switched off. To observe magnetization processes in applied magnetic fields, the standard objective lens can be slightly excited, leading to a magnetic field H_{pp}, which is perpendicular to the plane of the sample. Magnetic fields H in the plane of the dots then can be achieved by tilting the sample in the vertical field H_{pp}. Due to the large aspect ratio diameter/height of the investigated nanostructure elements, the field has only little effect and leads to a slight decrease of the vortex annihilation or saturation field H_s, as confirmed by micromagnetic simulations.

Figure 1 shows the introduction of a geometric asymmetry by “flattening” a circular disk so as to provide a flat or straight edge.

Figure 2 shows underfocused Lorentz microscopy images of the asymmetric dots at remanence after the application of a magnetic field $|H| = 200$ Oe in $-x$ (a) and in $+x$ direction (b). The spots originate from a vortex configuration in the magnetic dots. The bright spot corresponds to clockwise, the dark spot to counterclockwise

sense of rotation, due to the defocusing and focusing effect of the magnetization pattern on the electron beam, respectively.

Figure 2 shows the asymmetry in the shape of a circular dot by preparing disks (diameter d = 700nm) with one flat edge, thus breaking the in-plane isotropy of the circular dots. After saturation in fields H = ± 200 Oe parallel to the flat edge of the dots in -x (a) and +x direction (b), at remanence one finds bright (a) and dark spots (b) in the Fresnel images. Since the sense of magnetization rotation determines the contrast of the spot, the sense of rotation of all particles in Fig. 2(a) and (b), respectively, is the same and depends on the direction of the foregoing saturation field. In the underfocused images a bright spot corresponds to clockwise (cw), a dark spot to counterclockwise (ccw) sense of rotation.

Fig. 3 shows magnetization reversal of asymmetric dots with the in-plane field H applied parallel to the flat edge (x-direction). Inserted arrows indicate the direction of magnetization. (a) Saturation at H_s = -192 Oe; (b) at H_{ev} = -22 Oe a vortex with its center near the flat edge becomes visible; (c) remanent state with the vortex core in the dot center; (d) the reversed field yields a shift of the core to the curved edge; (e) at H = +112 Oe the vortex is fixed to the edge; (f) the vortex abruptly disappears at H = 192 Oe. In the opposite direction (g-l), the same mechanisms proceed, but the sense of rotation is reversed from clockwise to counterclockwise, visible by the change from bright to dark contrast inside the elements (c,i).

In Fig. 3 the evolution and annihilation of the vortices is shown coming from two oppositely oriented saturation directions: After the application of a sufficiently high magnetic field H = -192 Oe, all elements are saturated in -x direction (Fig. 3(a)), where no contrast can be observed inside the elements. Reducing H leads to the evolution of a vortex (cw) at H_{ev} = -22 Oe near the flat edge of the dot (b). The vortex core is then shifted towards the geometric center of the particle when the

field is decreased further towards H = 0 Oe (c). Reversing the field direction and increasing the field value yields a continuing shift of the vortex core to the curved edge opposite to the flat edge of the particle (d,e) until the Bloch line ins finally pushed out of the dot in a sufficiently high field (f), the saturation field H_s = +192 Oe. In this specification the saturated state is defined as a state where all magnetic moments are aligned approximately parallel, allowing small angle deviations from the mean magnetization direction especially at curved particle edges. Decreasing the field value from H_s = +192 Oe (Fig. 3 (g)-(l)) shows that the basic processes are the same, especially the evolution of the vortex near the flat edge of the particle, with one significant difference: the sense of magnetization rotation is reversed from cw to ccw.

To verify the dependence of the sense of rotation on the direction of H_s, the remanent magnetization of the elements during several magnetization reversal processes is investigated. The normalized number of observed particles times cycles results in a probability of 100% that the vortex of the single vortex element (SVE) has clockwise (counterclockwise) sense of rotation at remanence if the previously applied field $|H| \geq |H_s|$ is aligned in -x (+x) direction. Therefore, a SVE can be designed where the sense of magnetization rotation can be adjusted by saturating the dot in an applied in-plane field H larger than H_s and reducing the magnetic field below the vortex evolution field H_{ev}.

Fig. 4 shows the comparison of two nanostructures with different saturation fields which indicates the vortex core has to be annihilated in order to reverse the vorticity. At an applied field H = +176 Oe (a), the lower element is saturated (no contrast variation), whereas in the upper element the vortex core is still at the edge (arrow). In a field H = 0 Oe (b), the previously saturated lower dot has changed from cw to ccw sense, the upper dot is still cw oriented. At H = +192 Oe (c) both of the dots are saturated in +x direction leading to a cw sense of both dots

at remanence (d).

In Fig. 4 the variation of H_S for the individual elements is used to show that the elements indeed have to be saturated or homogeneously magnetized to reverse the sense of rotation. In Fig. 4(a), at H = +176 Oe the upper element still shows the Bloch line at the element edge (arrow), whereas the lower element is already saturated in +x direction. Reducing the field to H = +192 Oe yields an upper cw and a lower reversed ccw SVE (Fig. 4(b)). In Fig. 4(c), a field H = +192 Oe is applied, which is sufficiently high to saturate both elements. Reducing again H to 0 Oe shows that the sense of the previously already reversed lower particle does not change, but the upper element is now also reversed to ccw sense (Fig. 4 (d)).

Fig. 5 shows a model for the evolution of the vortex, without restricting, the present invention to this particular model. Decreasing the magnetic field from a saturated state (a, $|H| > |H_S|$), the spins at the element edge align parallel to the edge at fields $|H_{ev}| < |H| < |-H_S|$ and are tilted at the two corners of the flat edge (b), determining the sense of magnetization rotation below the evolution field $|H_{ev}|$ (c). In (d), the circular clockwise magnetization distribution, which causes the bright spot at the disk center in the underfocused Fresnel image, is drawn schematically.

The sense of rotation of the SVEs is always oriented in a way that the magnetization at the flat edge is antiparallel to the previous saturated state. This can be roughly explained as follows: Reducing the field from saturation (Fig. 5(a)), the spins at the dot edges deviate from the mean magnetization direction and align more and more parallel to the dot edges to avoid magnetic charges. (Fig. 5(b)). Since the curved edge is longer than the flat, straight edge, a preferred direction of the magnetization rotation is induced by the peripheral spins (Fig. 5(c)) and exchange coupling to the spins closer to the center leads to the formation of

the vortex with the given vorticity at the evolution field H_{ev}. In contrast to circular nanostructures, the sense of magnetization rotation of the presented SVEs can be controlled by the direction of the applied magnetic in-plane field.

The magnetic elements and memory cells of the present invention can be used in an MRAM and can be a component in the production process of an MRAM. Therefore, the structure and function of such an MRAM will now be briefly discussed.

An MRAM is a non-volatile memory whose information is carried by a memory cell which is a combination of ferromagnetic and non-ferromagnetic micro- or nanostructures. As shown in Fig. 6, the memory cell essentially comprises a hard magnetic electrode M1 and a soft magnetic electrode M2 which are separated by a non-ferromagnetic intermediate layer ZS which can be electrically conductive or isolating, e.g. a Al_2O_3 layer. The relative orientation of the magnetizations of the two electrodes M1 and M2 is decisive for the magnitude of the electric resistance of the memory cell, R_{SZ}.

The left-hand part of Fig. 6 shows a current-in-plane (CIP) geometry with current flow within the plane, whereas the right-hand side shows a current-perpendicular-to-plane (CPP) geometry with current flow perpendicular to the magnetic particles M1 and M2.

If one considers the special case that the two electrodes are homogeneously magnetized, and only two directions are allowed for the magnetization vector, e.g. +x and –x in a Cartesian co-ordinate system, the electric resistance R_{SZ} of the memory cell is low for a parallel orientation of magnetization of the two electrodes whereas for an anti-parallel orientation of the magnetization in M1 and M2 the electric resistance is high. The binary information consists of the electric

resistance R_{SZ} of the memory cell, e.g. parallel orientation and small R_{SZ} means "1" (see Fig. 7b), whereas anti-parallel orientation and consequently high electric resistance R_{SZ} means "0" (see Fig. 7c). In the CPP memory cell the electrical current I flows vertically through the memory cell, i.e. along the z-axis. The high and low electric resistance of an MRAM corresponds to the loaded and unloaded capacitor of a DRAM.

In the CIP arrangement, the intermediate layer ZS consists of a non-ferromagnetic metal, whereas in the CPP arrangement, the intermediate layer ZS may be a non-ferromagnetic, conducting material or an isolator. Presently, the CPP arrangement with a thin isolating layer, which acts as a tunnel barrier, is preferred for an MRAM. Memory cells with such a structure are known as magnetic tunnel contacts or magnetic tunnel junctions (MTJ). MTJs have the advantage that the total resistance of the memory cell is higher than when using a non-ferromagnetic intermediate layer ZS whose function is based on the giant magnetoresistance GMR. The magnetic elements of the present invention can, e.g., be used in CPP/GMR and CPP/MTJ memory cells.

The memory cells of the present invention can be arranged at the cross points of at least two conductor lines, usually called wordline and bitline, wherein the memory cell forms an electric connection of these conductor lines, as shown in Fig. 8, optionally together with a transistor. The addressing of the individual memory cells (bits) is done via the wordline and bitline since the electric current can only flow through those memory cells which are at the cross points of the word- and bitline. The value of ΔR depends on the relative orientation of M1 and M2, as discussed above.

The magnitude of the electric resistance which the electric current I undergoes when flowing through the memory cell, and which depends on the relative

orientation of the magnetizations in the two ferromagnetic electrodes M1 and M2, supplies the information concerning the magnetization state of the memory cell and thus the binary information.

The writing and erasing of information can generally be done in two different ways:

1. The superposition of magnetic fields which are produced by electric currents through the wordline and bitline results in a homogeneous magnetic field at those cross points at which the memory cell to be written is present. The resultant magnetic field is large enough and appropriately directed to switch the soft magnetic electrode of the memory cell, i.e. to produce a change in the relative orientation of the magnetizations in the two electrodes M1 and M2.

2. A current perpendicular to the memory cell, i.e. from the wordline to the bitline and vice versa, switches the soft magnetic electrode M2 either via spin injection or via the magnetic field produced by the current. This kind of switching requires memory cells whose electric current is small enough to allow the currents required to achieve the magnetic field for writing. CPP/GMR memory cells having a low electric current are therefore advantageous.

Switching via the magnetic field requires a magnetization pattern of the soft electrode M2 which has approximately the symmetry of the magnetic field. Thus, magnetic electrodes of the invention can be used which are circularly magnetized, i.e. which comprise a vortex magnetization.

The magnetic elements and memory cells of the present invention are geometrically formed such that in remanence after the application of a magnetic field, i.e. via the magnetic fields of the word- and bitline, they comprise a magnetic

vortex or vortex-like configuration with a controllable sense of magnetization. For writing, the current thus need not be lead through the memory cell. According to the invention, control of the sense of magnetization is achieved via a slight modification of the geometry of a structure which is generally rotationally symmetrical around the z-axis. In the present invention, the direction of magnetization of the magnetic layers M1 and M2 is considered the same when the sense of magnetization rotation of the respective vortex in both magnetic layers M1 and M2 is either clockwise or counterclockwise, whereas the magnetization direction is considered anti-parallel if the sense of magnetization rotation is clockwise in one magnetic layer and counterclockwise in the other magnetic layer.

The magnetization in the magnetic elements of the present invention is schematically shown in Fig. 9. Fig. 9 shows a top view of the hard magnetic electrode M1 and the soft magnetic electrode M2, respectively. With anti-parallelly oriented vortices in the electrodes M1 and M2, the electric resistance R_{SZ} in the memory cell is high whereas R_{SZ} is low with parallel orientation. A two-dimensional array consists of the periodic continuation of a linear array in both directions of the xy-plane.

The writing or addressing of the magnetic elements of the invention is carried out via the resulting magnetic field $H_{effective}$, which is generated by superposition of the magnetic fields which are generated by the currents through the wordline ($H_{wordline}$) and the bitline ($H_{bitline}$). As shown in Figs. 10a and 10b, the memory cell is provided at the cross points of the wordline and the bitline such that the resulting field $H_{effective}$ is correctly oriented with respect to the asymmetry of the magnetic elements. The writing of the information as such is known in the art. A memory cell according to the present invention can be embedded into known systems.

Fig. 11 shows a stack of layers comprising a plurality of magnet/non-magnet transitions which allow the generation of more than two values of the total electric resistance. In such a stack, more than one bit of information can be stored. The electric resistance of the stack depends on the relative orientation of the magnetization directions of each pair of two adjacent magnetic layers.

For the magnetic elements of the present invention, a multitude of magnetic materials can be used. It is preferred that the materials in the asymmetric geometry of the present invention comprise a closed magnetic circuit or a ring circuit in remanence upon application of a magnetic switching field, for example in the form of a magnetic vortex, a Landau-Lifshiftz-domain configuration or similar magnetizing configurations. Such materials are, for example, iron, nickel, cobalt and their alloys. Thus, in the present invention, temperature-sensitive magnetic materials, like e.g. artificial or natural anti-ferromagnetic materials are not required in the hard magnetic electrode M1. Thus, the magnetic element and memory cell of the present invention can be produced and used at high temperatures up to the melting temperature of the used materials. Temperatures of less than 300°C are, however, preferred in order not to affect the magnetic properties of the used materials by diffusion effects. Generally, all materials and material combinations can be used which are applicable in MRAMs.

Claims

1. Magnetic element comprising a magnetization pattern having a magnetic flux closure in remanence, wherein the magnetic element is asymmetric and the sense of magnetization rotation is controllable by means of an applied magnetic field.

2. Magnetic element according to claim 1, wherein the magnetization pattern is a magnetic vortex-like configuration.

3. Magnetic element according to claim 1 or 2, wherein the magnetic element comprises a generally circular, disk-like structure having a slight geometric asymmetry.

4. Magnetic element according to claim 3, wherein the magnetic element is circular disk-shaped with a flat edge.

5. Magnetic element according to claim 4, wherein the length of the flat edge is about 1/4 to 3/4, preferably about 1/2 to 2/3 of the disk diameter.

6. Magnetic element according to claim 4 or 5, wherein the disks have a diameter of about 100-2000 nm, preferably 200-1000 nm, more preferably about 400-900 nm, most preferably about 600-800 nm.

7. Magnetic element according to any of claims 4 to 6, wherein the thickness of the disk is about 1-20 nm, preferably about 5-9 nm.

8. Magnetic element according to any of claims 1 to 7 which comprises at least one magnetic particle.

9. Magnetic element according to claim 1, wherein the magnetization pattern configuration is stable against magnetic fields that are smaller than the saturation field of the element.

10. Magnetic element according to any of claims 1 to 9, wherein the magnetic element has substantially zero remanent magnetization.

11. Magnetic element according to any of claims 1 to 10, wherein the magnetization pattern configuration is produced by magnetization in an in-plane magnetic field up to saturation.

12. Magnetic element according to any of claims 1 to 11, wherein the magnetic element comprises Fe, Ni, Co, and/or alloys thereof.

13. Method of producing the magnetic element of any of claims 1-12, wherein the magnetic elements are formed on electron transparent membranes by a combination of electron beam lithography and liftoff technique.

14. Memory cell comprising at least one magnetic element according to any of claims 1-12.

15. Memory cell according to claim 14 having two senses of magnetization rotation which define one bit of information.

16. Memory cell according to claim 14 or 15, wherein the memory cell comprises a stack of at least two magnetic elements with different saturation fields to define a multi-bit data storage cell.

17. Memory cell according to any of claims 14 to 16 which is a non-volatile memory cell.

18. Memory cell according to any of claims 14 to 17 which is a magnetic random access memory (MRAM) cell.

19. Memory cell according to any of claims 14 to 18, wherein the memory cell is a giant magnetoresistance, spin valve or magnetic tunnel junction memory cell.

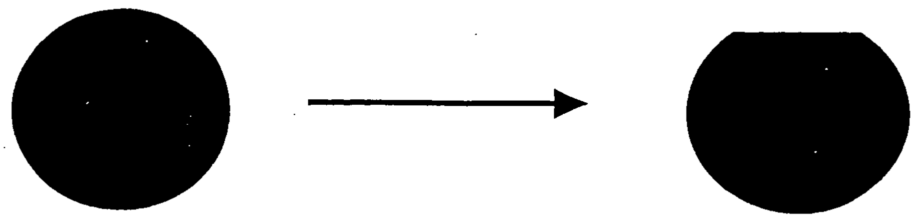


Fig. 1

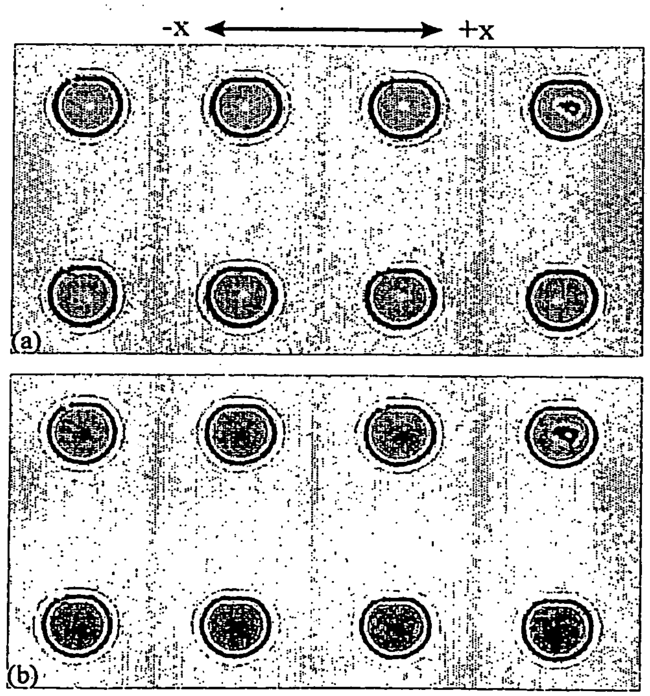


Fig. 2

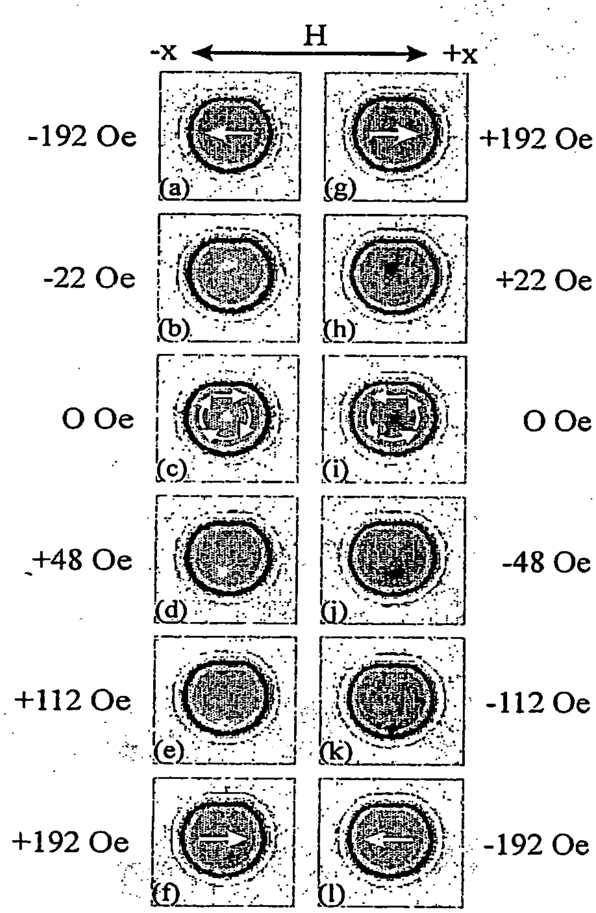


Figure 2

Fig. 3

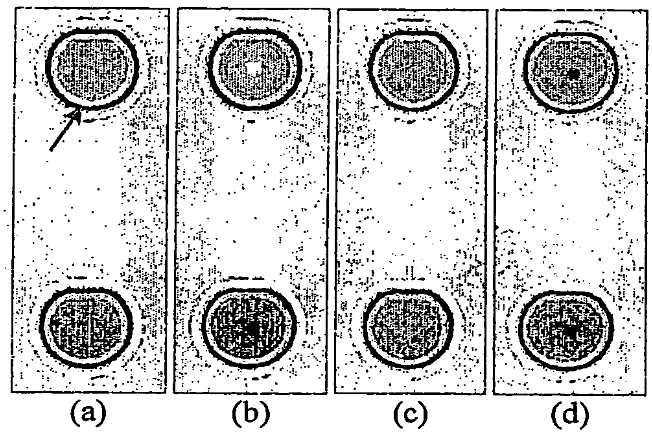


Figure 3

Fig. 4

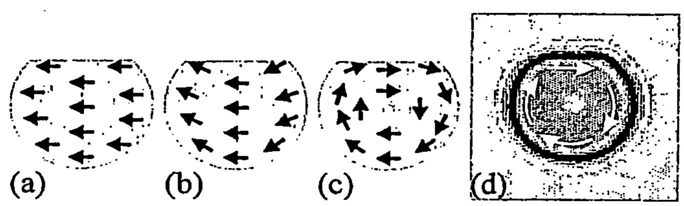


Fig. 5

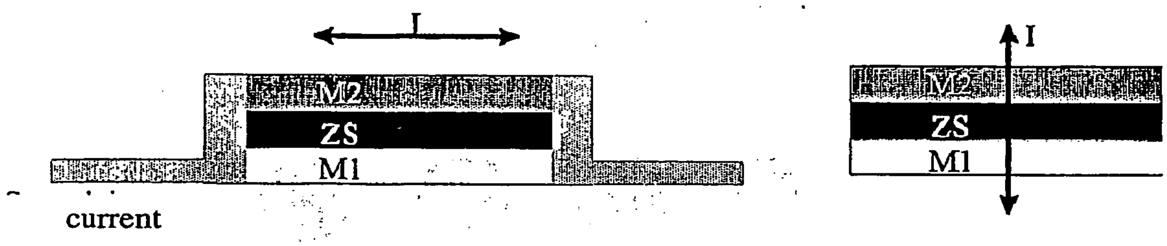


Fig. 6

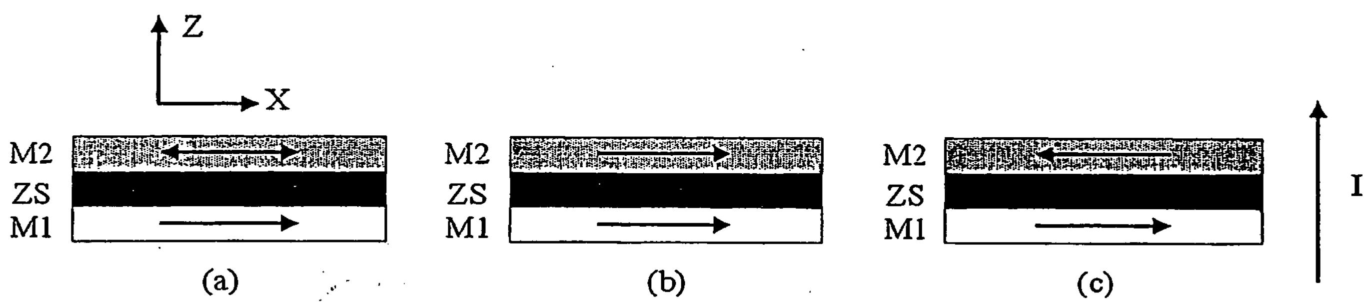


Fig. 7

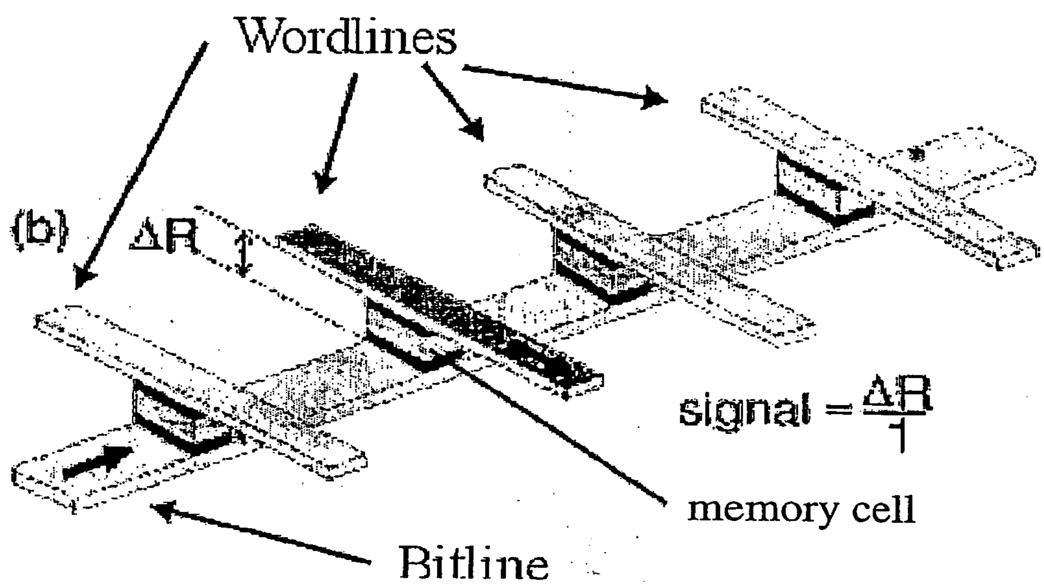

Wordlines
(b)
ΔR
signal = ΔR/1
memory cell
Bitline

Fig. 8

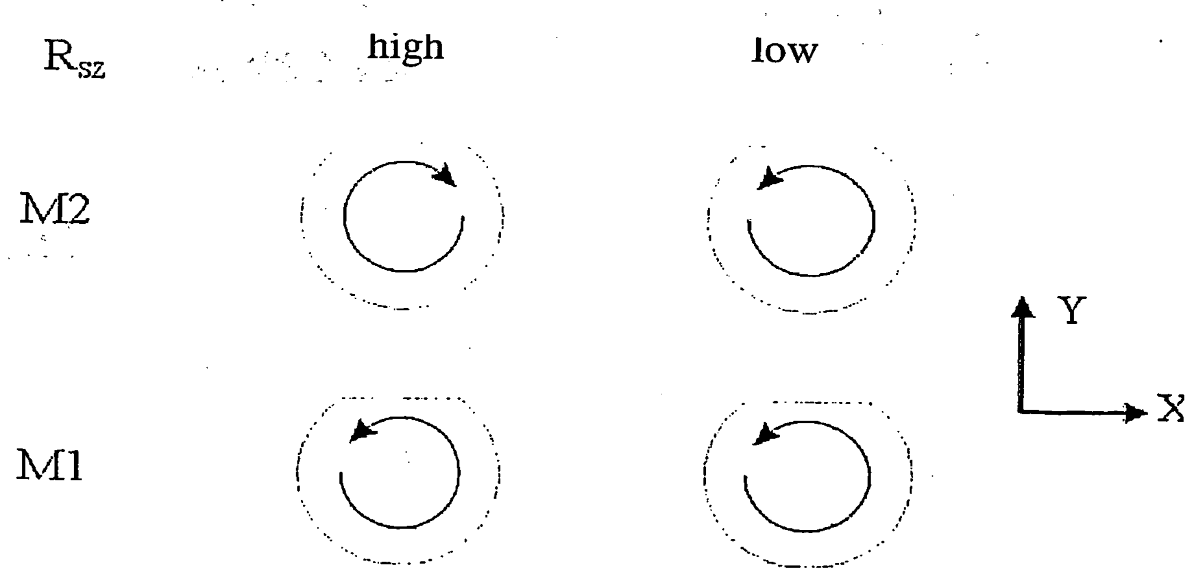

R_SZ
high
low
M2
M1
Y
X

Fig. 9

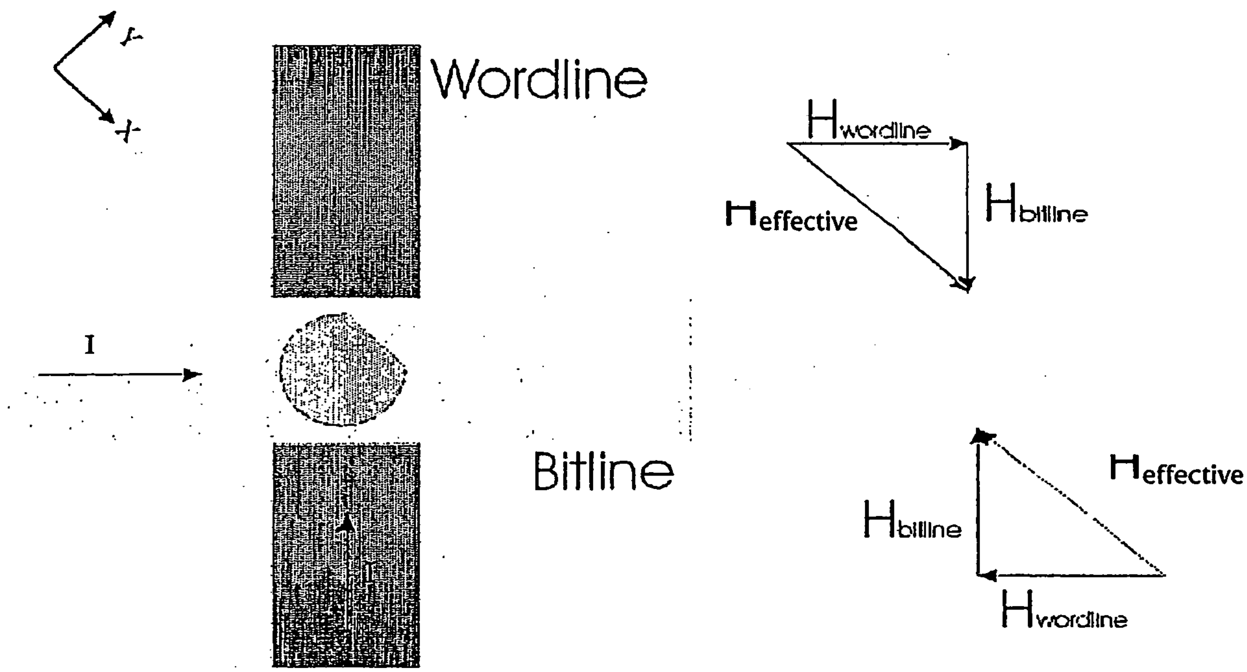


Fig. 10A

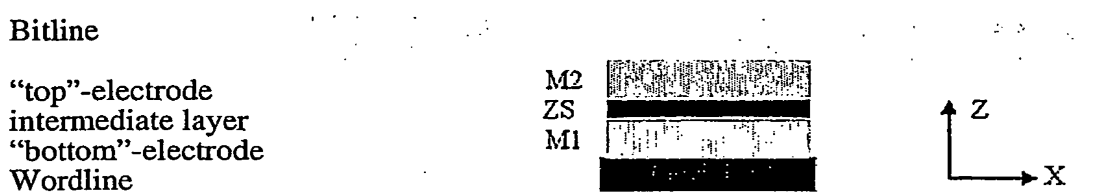


Fig. 10B

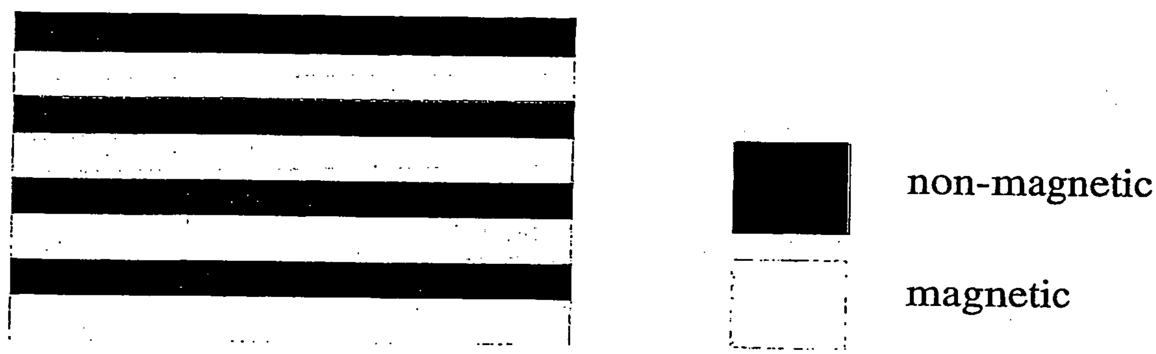


Fig. 11

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 02/11168

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01F1/00 G11C11/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HIROHATA A ET AL: "MAGNETIC DOMAIN EVOLUTION IN PERMALLOY MESOSCOPIC DOTS" IEEE TRANSACTIONS ON MAGNETICS, IEEE INC. NEW YORK, US, vol. 35, no. 5, PART 2, September 1999 (1999-09), pages 3886-3888, XP000868087 ISSN: 0018-9464 page 3886, column 2, paragraph 2; figure 1B page 3887, column 1, paragraph 3; figure 2B page 3888, column 1, paragraph 2 ---	1-3,6-8, 10-12

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 February 2003	12/02/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Decanniere, L

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	SCHNEIDER M ET AL: "LORENTZ MICROSCOPY OF CIRCULAR FERROMAGNETIC PERMALLOY NANODISKS" APPLIED PHYSICS LETTERS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 77, no. 18, 30 October 2000 (2000-10-30), pages 2909-2911, XP001133809 ISSN: 0003-6951 cited in the application page 2909 page 2910, column 2, paragraph 1; figure 3	1-3,6-13
A	RAABE J ET AL: "MAGNETIZATION PATTERN OF FERROMAGNETIC NANODISKS" JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 88, no. 7, 1 October 2000 (2000-10-01), pages 4437-4439, XP001049061 ISSN: 0021-8979 cited in the application page 4437; figures 1,2	1-3,6,8, 12,13
A	WO 00 58970 A (UNIV CARNEGIE MELLON) 5 October 2000 (2000-10-05) cited in the application claims 1,4,6-10,18-20; figures 7,9	1-3,8, 16-19

INTERNATIONAL SEARCH REPORT

Interna pplication No
PCT/EP 02/11168

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 0058970	A	05-10-2000	US	6391483 B1	21-05-2002
			WO	0058970 A2	05-10-2000

Form PCT/ISA/210 (patent family annex) (July 1992)